



Drainage water salinity and quality across nested scales in the Nile Delta of Egypt

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Received: 29 April 2019 / Accepted: 21 November 2019 / Published online: 24 December 2019
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Abstract

Improving water management depends on understanding the functioning of irrigation and drainage systems across different environmental scales. For this purpose, this study in the Nile Delta of Egypt particularly examines the spatial and temporal variation of drainage water salinity from the system to the plot level. A better understanding of this variation across nested scales is crucial to refine the government's drainage reuse strategy and reduce the adverse effects on agricultural productivity, lagoon ecology, and human health. The study investigates the drainage system of the Meet Yazid study area (82,740 ha) located in the upper central part of the Nile Delta. The parameters measured were electrical conductivity (EC), dissolved oxygen (DO), pH, and temperature. Results showed that salinity and quality of drainage water in the Nile Delta vary highly with space and time. The secondary drains exhibited the highest variability of salinity compared with main drains and subsurface drainage collectors because they accumulate salts from deeper soil layers and seepage of saline groundwater at the time of low flow discharge. In secondary drains, the salinity increased up to four times that of drainage water coming from the collectors. Moreover, DO values were most of the time not meeting standards for reuse in irrigation, especially at main drains that collect not only agricultural drainage but also untreated household sewage water.

Keywords Drainage · Salinity · Water quality · Spatial and temporal variability · Egypt · Nile Delta

Introduction

In irrigation management, a particularly complex environmental issue is the relationship between water quality and quantity at macro (system), meso (intermediate), and micro (plot) levels of drainage. To better understand the spatial and temporal variation of drainage water quality across these nested scales is needed to reduce the adverse effects of reusing drainage water on agricultural productivity, natural

ecosystems, and human health. We will investigate this issue in the central part of the Nile Delta in Egypt, proximate to its Northern Coast.

The drainage system in Egypt consists of a network of open main, secondary drains and subsurface drainage pipes at the field level. Pump stations at the end of the drainage system lift the collected drainage water to the level of the Northern lagoons (also referred to as lakes) and the Mediterranean Sea. Following on from these lifting points and surrounding the lagoons lies a zone of fish farms with aquaculture activities, which reuse the saline drainage water before releasing it to the lagoons. After completion of the Aswan High Dam in 1970 and the development of year-round irrigated agriculture, developing an artificial drainage system became urgent in order to control waterlogging and salt accumulation in the root zone (Ali et al. 2001). A national program launched in the 1960s implemented a pilot project for the drainage of agricultural lands. Recently, the bulk of the delta has been covered with subsurface drainage pipes (Nijland et al. 2005). These pipes are usually set at a depth of 1.25 m from the highest point of the field with a minimum spacing of 30 m. Therefore, the bed level of the open drain is required to be at least 2.5 m below

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the field ground level to allow proper drainage (IWMI and WMRI 2013) (Fig. 1). The pipe collectors release their discharge into open secondary drains and then to main drains, from where the drainage water is pumped into large open gravity drains which eventually discharge into the lagoons or the Mediterranean Sea.

Drainage water salinity is a major water quality concern for agricultural water management in arid countries like Egypt. Reuse of drainage water with high salinity affects the sustainability of the irrigation system. Farmers irrigate from canals but also from drains, and by doing so they bring a higher concentration of salts onto their plots, which affects crop yield (El-Ganzori et al. 2000). Many factors influence the salt concentration in drains, such as the quantity and quality of irrigation water, type of soil, and type of crop. Across nested scales, salinity has an impact on drainage water reuse by agricultural farmers, fish farmers, and fishermen in the lagoons. Several studies further indicate that the disposal of large quantities of agricultural, industrial, and municipal wastes through several main drains causes the degradation of the Northern Delta lakes water quality (Maclaren 1982; Beltagy 1985; Bebars and El-Gammal 1986; Moussa 2003; El-Zeiny and El-Kafrawy 2017). Within the Nile Delta region, four natural lagoons are located: Burullus, Manzala, Edku, and Maryut, of which the first lies in the Central Nile Delta. These lakes are directly connected to the sea, host a rich ecosystem, and have a unique environmental value.

A better understanding of both the spatial and temporal variation of drainage water quality in the Delta becomes crucial. The Ministry of Water Resources and Irrigation (MWRI) is currently monitoring water quality at 106 sites located at the main drains. The Drainage Research Institute (DRI) is responsible for collecting data monthly, with 24 parameters of water quality (Abdel-Dayem 2011). The current relatively coarse and static monitoring system only collects data at the main drains (macro) on a monthly basis, while data on the secondary and tertiary drains (meso/micro) are not collected. The MWRI strategy emphasizes the reuse of drainage water for irrigation purposes to face water shortage especially in the

northern part of the Nile Delta. Therefore, knowledge about drainage water quantity and quality and pollution sources at various levels is essential to reduce the adverse effect of reusing drainage water on soils, crops, fisheries, and the lagoons.

Drainage water salinity is one of the main environmental challenges for the reuse strategy in the Northern Nile Delta. The Nile Delta generates drainage water with a salinity roughly three times larger than the irrigation water brought into the delta by the Nile River, while this ratio increases in the northern part to reach about 5 to 10 or more (Roest 1999; Zhu et al. 1996). Many studies related this phenomenon to salt groundwater intrusion from the Mediterranean Sea and upward seepage generated by local hydraulic conditions (Kashef 1983; El-Kady and Molden 1995; MWRI 2005; Morsy 2009; Kotb et al. 2000; Nofal et al. 2015). Cultivation of rice and aquaculture activities are the only mitigation measures currently practiced in the northern part of the Nile Delta to keep soil salinity at acceptable levels (Molle et al. 2019).

Earlier studies investigated drainage water salinity at the plot level and its relation to irrigation water salinity in different locations of the Nile Delta. Abd El Aleem (1990) and El-Atfy et al. (1999) found ratios of drainage vs. irrigation water salinity ranging from 4.2 to 6.5. In addition, an experiment conducted with good quality irrigation water (340 μmhos) by Abdalla et al. (1990) found a salinity at the outlet of the main subsurface drainage collector varying between 2500 and 7500 μmhos , corresponding to a high ratio (between 10 and 20) due to high salt content of the clay layer located below the drainage lines. According to a survey done by APRP (2002), the average salinity of drainage water in Egypt increased from 2.4 g/l in 1985 to 2.75 g/l in 1995 with some local variations. For instance, in the southern part of the Nile Delta, drainage water had salinity between 0.75 and 1.0 g/l, whereas the salinity in the middle parts of the Delta reached about 2.0 g/l and in the northern parts between 3.5 and 6.0 g/l. This salinity level at the north of the Nile Delta is problematic and needs more investigation.

The current study aims to map and understand the spatial and temporal variability of some drainage water quality parameters across nested scales. Identifying the sources of drainage water degradation will improve water availability at the tail end of the system that suffers from water shortage. Also, it will help policymakers to manage land, water, aquaculture, and agriculture in this region more effectively and thus reduce the adverse impact on the environment and human health.

Methodology

To understand the variability of drainage water quality at different scales (micro, meso, and macro) of the drainage system, a study area was selected in the upper central part of the Nile Delta. At

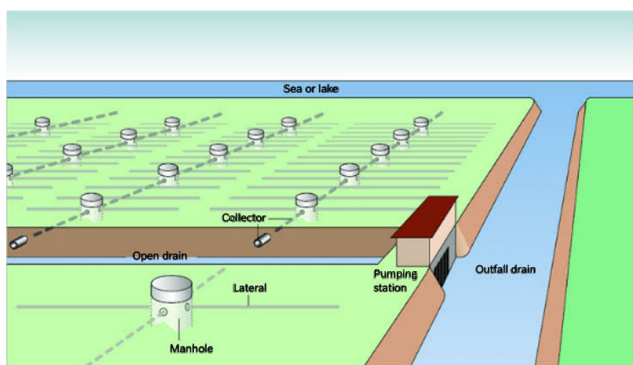


Fig. 1 Schematic representation of subsurface drainage (Abbott and El Quosy 1996)

the macro level, the drainage system of the Meet Yazid Canal (MYC) command area (82,740 ha) was investigated. The physical and environmental characteristics of the MYC command area are similar to those of the entire Nile Delta. The drainage system of the study area ends with pump stations lifting the drainage water to Lake El-Burullus, which is reported by several earlier studies to be suffering from pollution (Bebars and El-Gammal 1986; Abdel-Moati and El-Sammak 1997; Sammak and El-Sabrouti 1995; Hereher et al. 2011 and Ali 2011).

At meso and micro levels, an area of 480 feddan (200 ha) was investigated and equipped with sensors to measure water levels and EC-values in canals and drains serving the area. The area that irrigates from Mares El-gamal branch canal was equipped with three sensors to measure water levels and EC at the head of the irrigation canal and one-third of the secondary drain length (El-Bashair drain). EC levels were also measured in subsurface drainage manholes as shown in Fig. 2. Besides, the study area’s cropping patterns data for winter and summer 2014/2015 were collected.

At macro level of the study area, multiparameter portable meters with GPS measured in situ 482 samples in summer 2014 along 24 drains. The winter survey focused on the downstream part only (149 samples) because the salinity values in the summer season survey were quite low and rather even in the upstream part of the command area. Moreover, in order to improve the knowledge of temporal salt dynamics in the northern part of the Nile Delta, we monitored drainage water salinity and water levels in the two main drains (drain no. 7

and 8) using water level and electrical conductivity (EC) meters equipped with data loggers storing hourly data (Fig. 2).

The parameters measured were salt concentration as measured by electrical conductivity (EC), dissolved oxygen (DO), pH, and temperature. The EC, DO, and pH values were interpolated using the kriging method in ArcGIS to produce the spatial distribution across the study area.

Results and discussion

The cropping patterns of the study area for winter 2014/2015 and summer 2015 (Fig. 3) show that the main crops were rice, cotton, maize and watermelon in summer and wheat, sugar beet, and clover in winter. Rice occupied about 50% of the area in summer, and the predominant crop in winter was sugar beet with about 40% of the area. The crops were spatially distributed over small fields with an average area of 0.4 ha, and each drainage collector received water from various field crops.

Variability of EC

The “meso level” area was irrigated with water of an EC equal to 440 μmhos on average, while the EC measured in the different manholes of the sub-drainage system at the same time varied much more than what was expected (Fig. 4a, b). The relationship between the salinity of applied irrigation water and the drained water via the subsurface drainage system

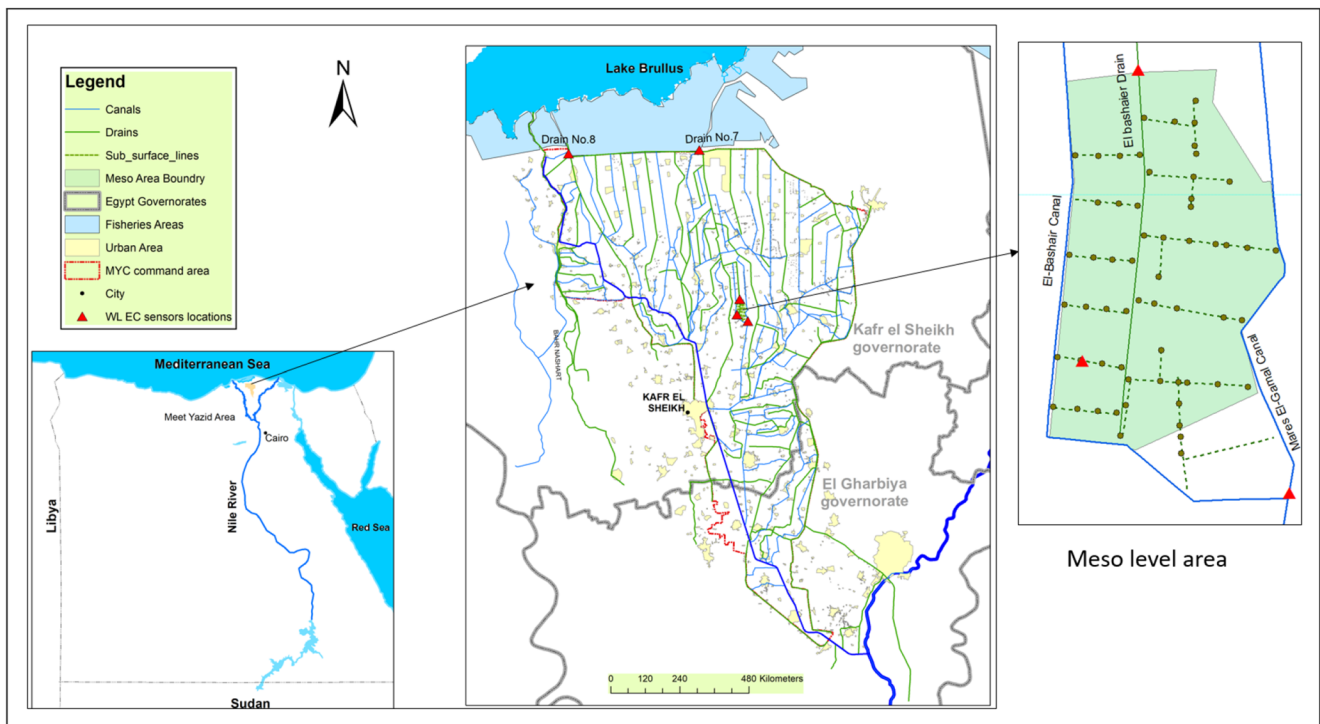


Fig. 2 Location map of the study area

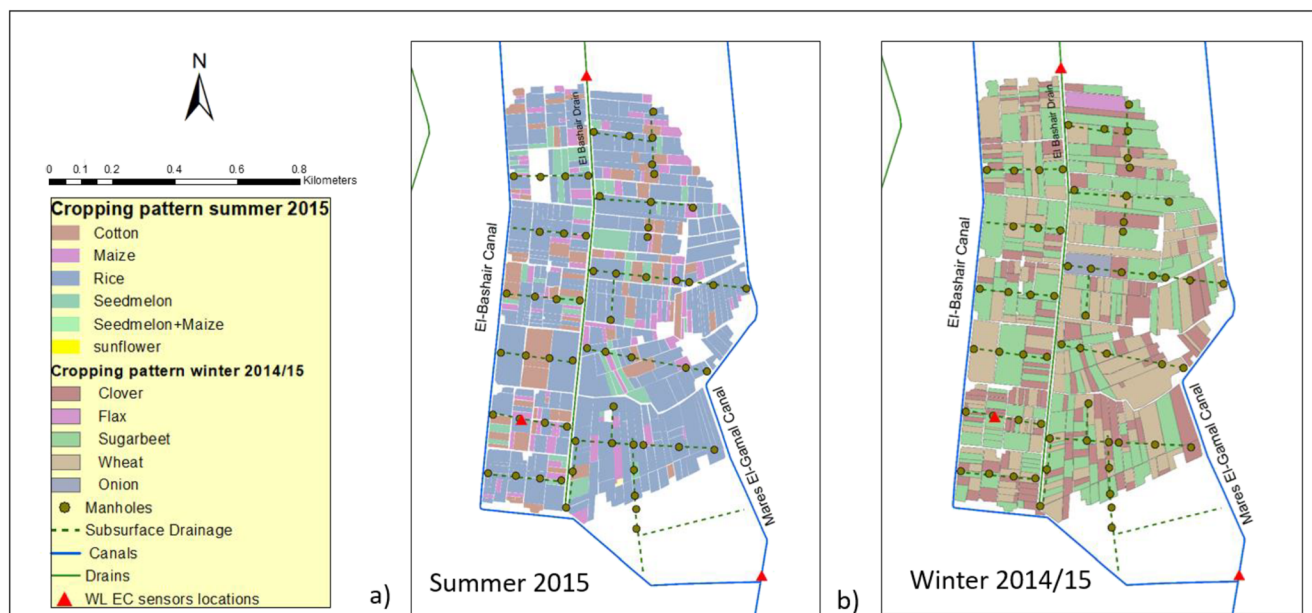


Fig. 3 Cropping pattern for meso area winter and summer seasons 2014/2015

varied substantially. The ratio between the two depends on the type of soil and its salinity, the cultivated crop, the irrigation method, the management, and the status of the subsurface collectors. Figure 4 shows the spatial variability of EC measured in the manholes of the study area which varied within a ratio between 1 and 10. This high range of variability is much more than what one would expect in a rather small area. In winter, 2014/2015 the EC values varied from 1000 to 9600 μmhos , and in summer the EC values varied less and at lower values between 660 to 4500 μmhos . The season has a clear effect because rice in summer consumes higher volumes

of water that leach the soil and reduce the drainage water salinity (Fig. 4a). Therefore, this variability reflects the type of soil and the amount of irrigation water applied (which defines whether salts are being leached or not), but the status of the subsurface drainage collectors (clogged up or not) and the semi-artesian nature of the aquifer in the northern part of the Delta are the most affecting factors. The red color, shown in (Fig. 4b), indicates EC values greater than 6000 μmhos that were attributed to clogged up collectors.

Further, one manhole in the subsurface drainage system was equipped with a sensor to measure the EC every

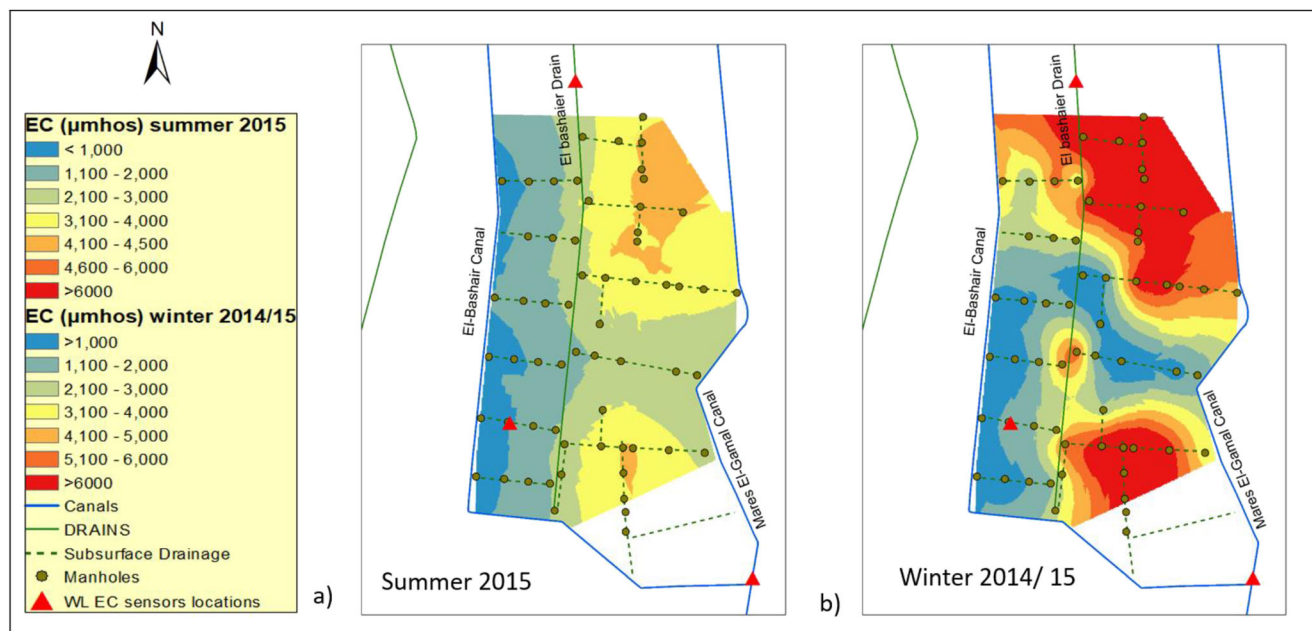


Fig. 4 Spatial variability of EC at manholes of meso area in summer 2015 and winter 2014/2015

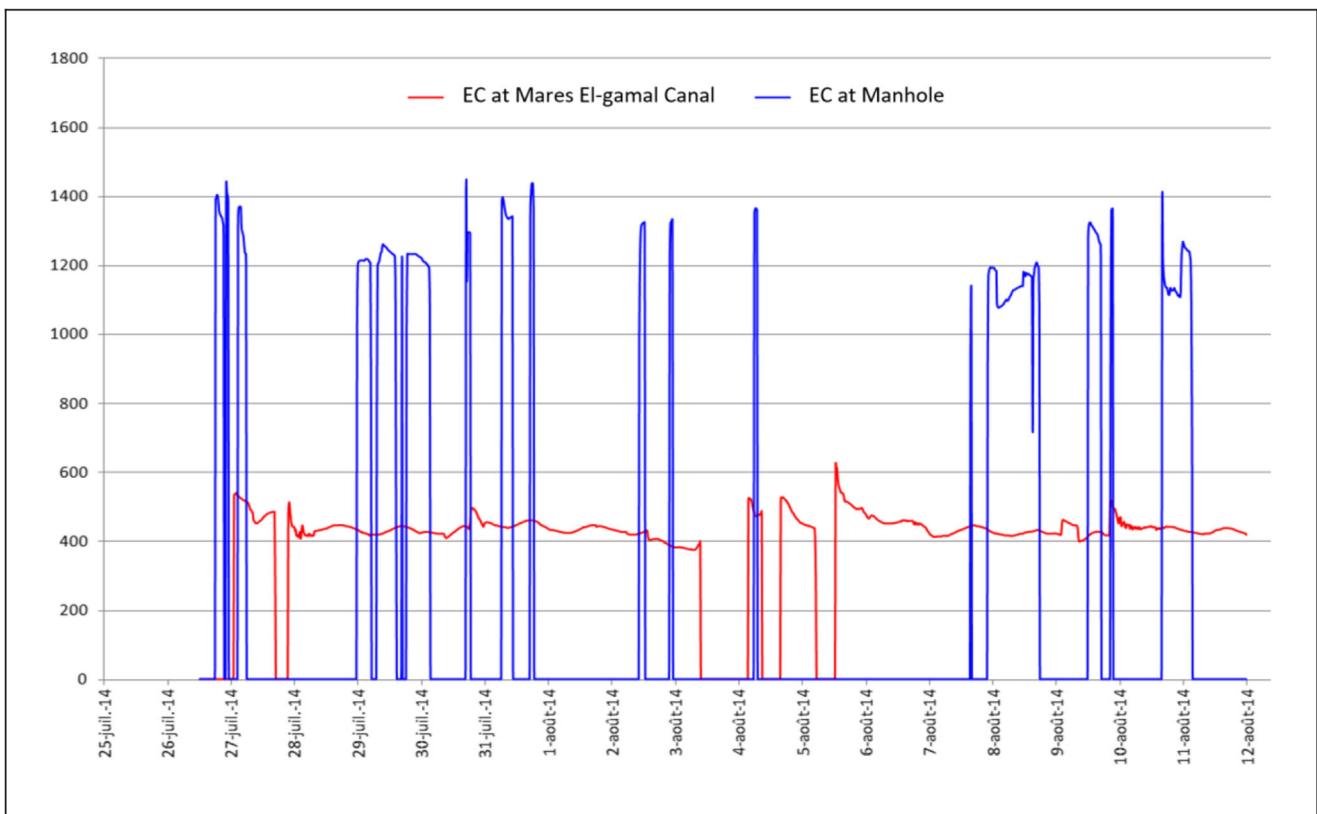


Fig. 5 Temporal variability of EC (µmhos) in canal versus values measured at a manhole

15 min. Measurements were discontinued when, a few hours after irrigation, the collectors dried up. Figure 5 shows this interrupted pattern from July to October 2014 (excluding extreme values at the beginning and end of each irrigation time). The data indicate that the salinity in the drainage collector is rather stable; the EC was varying between 1200 and 1400 µmhos in the manhole, three times the EC of canal irrigation water (Mares El-gamal) which was 440 µmhos (Fig. 5). This ratio of three is very consistent with previous studies (Roest 1999; Zhu et al. 1996; Abd El Aleem 1990) and illustrates the concentration of salts in the drained fraction.

The EC of drainage water in the secondary Bashair drain, to which our study area discharges, has been measured every 15 min during 1 year (Fig. 6¹). The EC values in the drain varied from 1500 to 5500 µmhos during summer. During winter, the EC varied more, from 927 to 7480 µmhos, in response to successive irrigation events. This means that the salinity in the secondary drain ranges from 3 to 17 times that of the irrigation water (440 µmhos). Also, the drain water salinity increases with lower water levels of Mares El-gamal canal in the winter season as shown in Fig. 7. Salinity results from a mix of surface tertiary drain (~0.6 mmhos), subsurface drain (~1.2–

5.0 mmhos), and lateral seepage from deeper layers (~3–6 mmhos or more). When the drains are almost dry (outside irrigation periods), lateral seepage provides most of the water to the drain, so that salinity increases dramatically (Fig. 7). A 2014/2015 survey of the Agricultural Research Center (ARC 2015) for the same area recorded an increase in groundwater salinity with depth from the ground surface. Furthermore, soil salinity in the area estimated by using a time-domain reflectometry (TDR) indicated for the winter season salinities of 3.1 mmhos in the surface layer, 4.6 mmhos in the subsurface layer, and 6.1 mmhos in the deep layer (ibid.).

At the macro level, the EC values of summer 2014 shown in Fig. 8a indicate that the upstream part of the study area had an EC lower than 1400 µmhos. The EC values increased northward (downstream) until reaching 4100 to 5400 µmhos at El Moheet drain. This drainage water is then lifted by pump stations to downstream aquaculture areas after which it flows to the Burullus Lake.

The EC values of one particular area draw attention. Most of the upstream drains had EC values lower than 1400 µmhos in summer except a low-lying swamp area visible in ancient maps called Matboul area, which had EC values ranging from 1500 to 2000 µmhos. It is possible that despite the cultivation of these areas for decades, the salt accumulated in the soil profile of this area has not been fully leached, but also that

¹ The sudden hike recorded during October and November is dubious. It is possibly due to some problems with the sensor during that period.

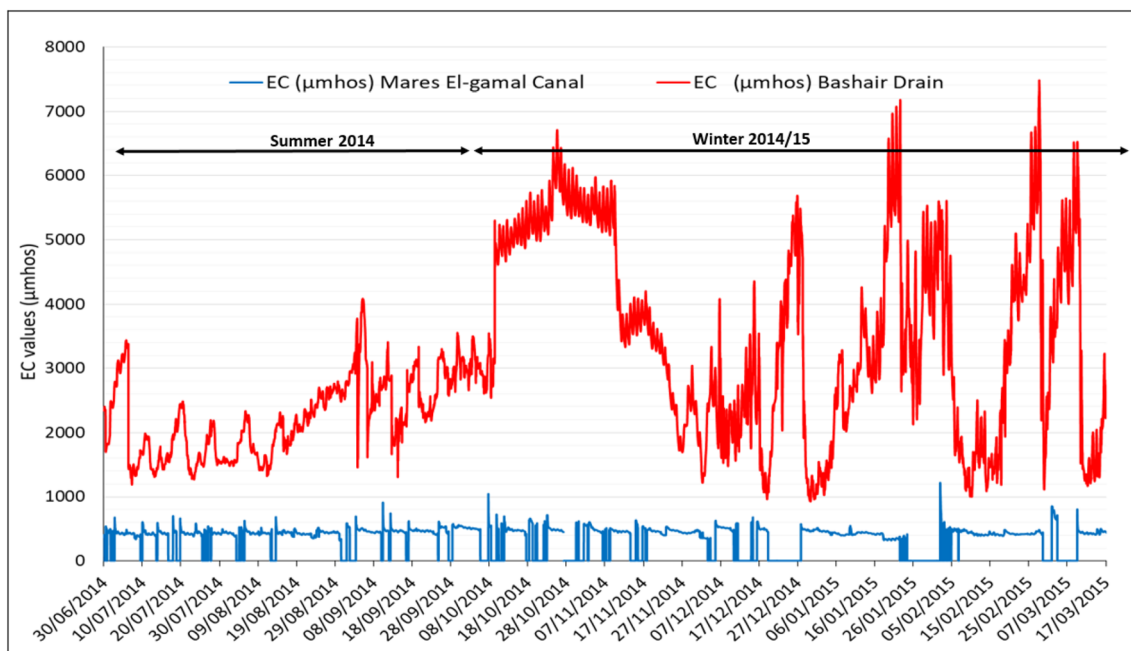


Fig. 6 Comparison of hourly EC (µmhos) values at canal and secondary drain in summer and winter 2014/2015

the depression promotes the upward seepage of salt by capillarity (Molle et al. 2018). The salinity values measured for the winter season show a substantial increase in almost all of the drains compared with the summer season values (Fig. 8b). If we limit ourselves to the downstream area surveyed in winter,

we find that the average EC of drainage water was 3033 µmhos in winter, against 2333 µmhos in summer, which indicates an increase of about 33%. In summer, higher amounts of irrigation and drainage water associated with the Nile regime dilute salinity and therefore decrease EC values.

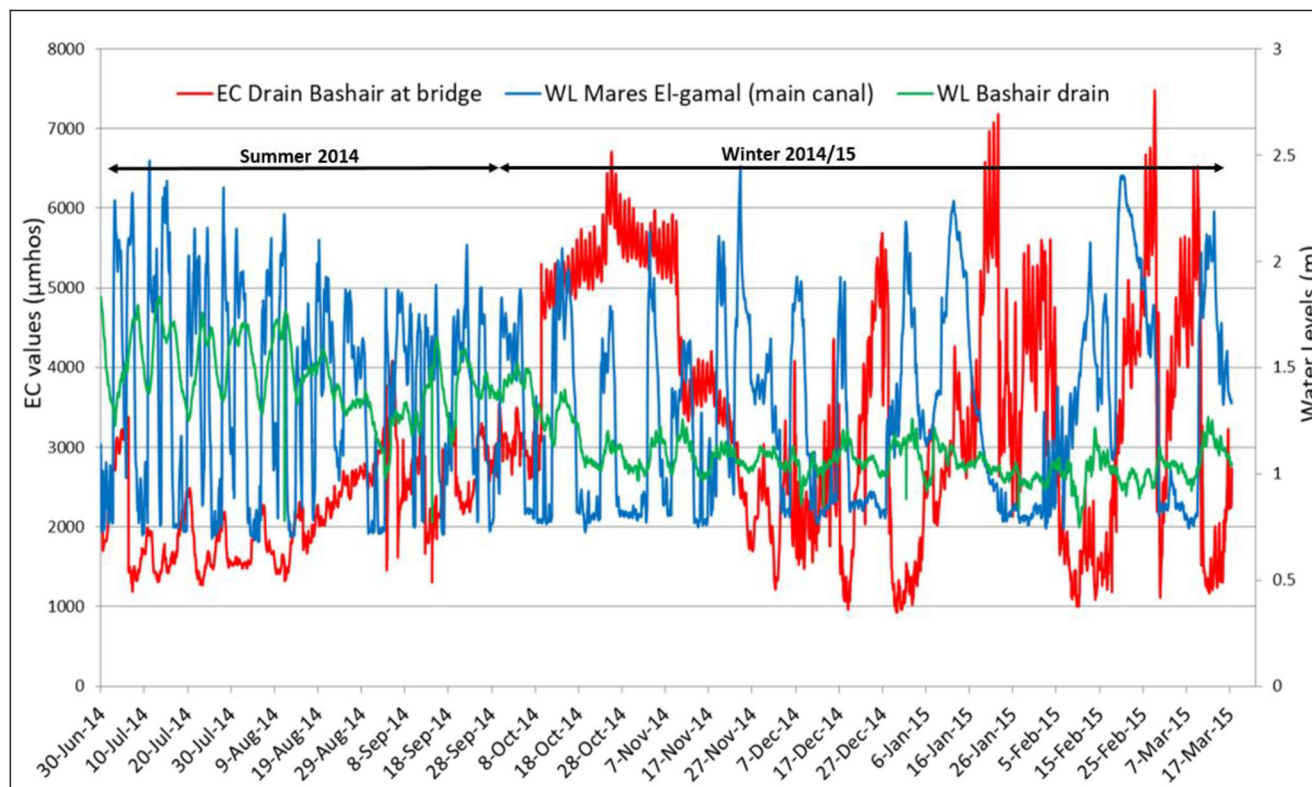


Fig. 7 The relation between water levels at canal, drain and EC (µmhos) values at the secondary drain

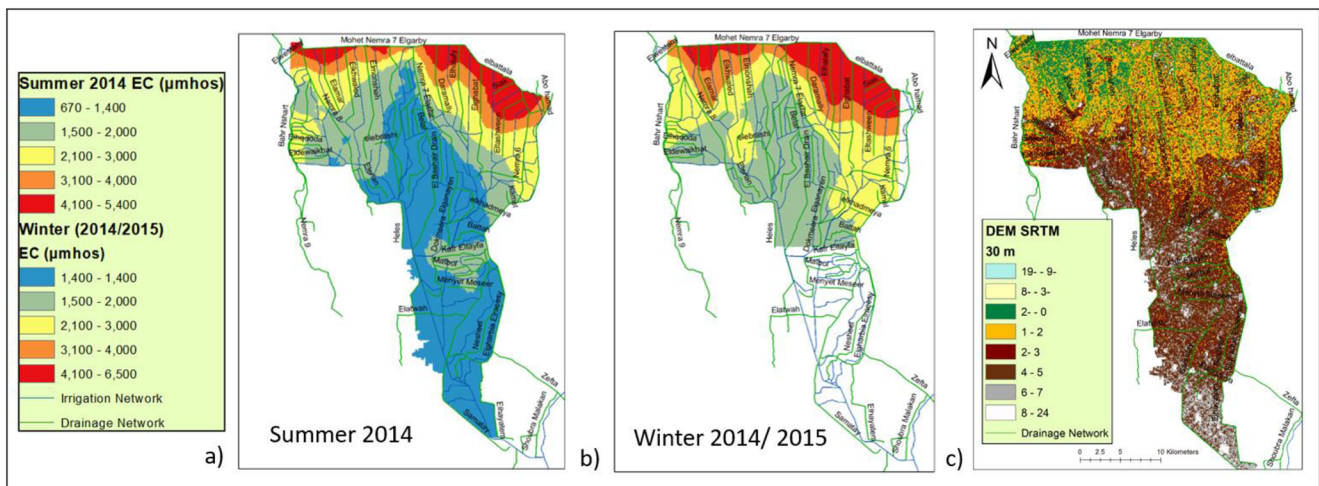


Fig. 8 Spatial distribution of water salinity in drains summer and winter 2014/2015

Moreover, deep soil layers drain its higher salt content to the drains when water levels in canals and drains become lower during winter. The Nile Delta topography ranges from 18 m above mean sea level (AMSL) in the south at the Delta apex to 5 m near the middle and sloping northward direction by an average value of 1 m/10 km (Saleh 1980). The digital elevation model of the study area (30 m resolution) indicated a clear relationship between the elevation of lands and the degree of drainage water salinity from these lands located in the northern Nile Delta (Fig. 8c). For instance, El-Monshaa, El-Khwaled, and El Amar drains located at land levels lower than sea level (0 to -2 m) produced drainage water with EC reached 6500 µmhos in the winter season (Fig. 8b).

Many studies indicated that there is highly saline groundwater in the northern part of the Nile Delta due to seawater intrusion in the subsoil (Ebraheem et al. 1997; Farid 1980; Mabrouk et al. 2013; Mabrouk et al. 2018). A recent study by Van Engelen et al. (2018) investigated different assumptions for the origin of hypersaline groundwater in the North of the Nile Delta and concluded that it can originate from induced upward salt transport, which formed during a geological event in which the Mediterranean Sea partly or nearly went into complete desiccation.

Surprisingly, EC values varied much more in some secondary drains than in the main drains. At the macro level, the pumping stations on main drains no. 7 and 8 dispose of the drainage water into farm fish areas, which is pumped out then to El-Burullus Lake. To monitor the temporal variability, hourly EC data downstream of pump station 7 and upstream of pump station 8 were measured. Figure 9 compares hourly EC values at the Mares El-gamal canal, secondary Bashair drain, main drains No.7, and main drain No.8 for the period from December 2014 to February 2015. The EC values for the secondary drain varied from 930 to 7176 µmhos. At the main drain no. 7 EC values varied from 1661 to 5636 µmhos, while at drain 8 between 1472 and 4836 µmhos. This is because the

main and northern-most drains receive water from the whole delta, and therefore their average salinity is lower than particular northern secondary drains (especially when these are situated at a very low level).

Variability of dissolved oxygen

DO is a measure of how much oxygen is dissolved in water, which informs us about water quality and degree of pollution. The amount of dissolved oxygen is essential for maintaining the biological life and organisms living in the water. Rapidly moving water such as in rivers has a higher concentration of dissolved oxygen than stagnate water such as in lakes. In addition, temperature affects the level of dissolved oxygen, and cold water holds more dissolved oxygen than hot water (Rounds et al. 2013). Abdel-Dayem et al. (2007) indicated the legally permitted water quality levels for drainage water reuse in agriculture, specified in law 48/1982 (Article 51, amended in 2013). The DO values should not be less than 5 mg/l and pH should be from 6.5 to 8.5.

At the meso level, in situ measurement of DO values took place in manholes of subsurface drainage. The water temperature in these stagnant waters was quite similar in both winter and summer seasons and varied from 20 to 27°C. Most of the DO values measured at the manholes were higher than 5 mg/l, which meets the legal norm. At the macro level, the main drains of Meet Yazid command area had too low DO values (less than 2 mg/l) in both summer and winter seasons upstream and downstream in the command area (for instance, drain No. 8, drain No. 7 and Samatay drain) (Fig. 10). Such values indicated an increase in organic matter, which comes from dumping untreated sewage of villages and cities directly into the drainage system. In addition, secondary drains downstream of the study area had very low DO values (less than 2 mg/l) in the summer season, while the values increased in the winter season upstream of the study area, as water

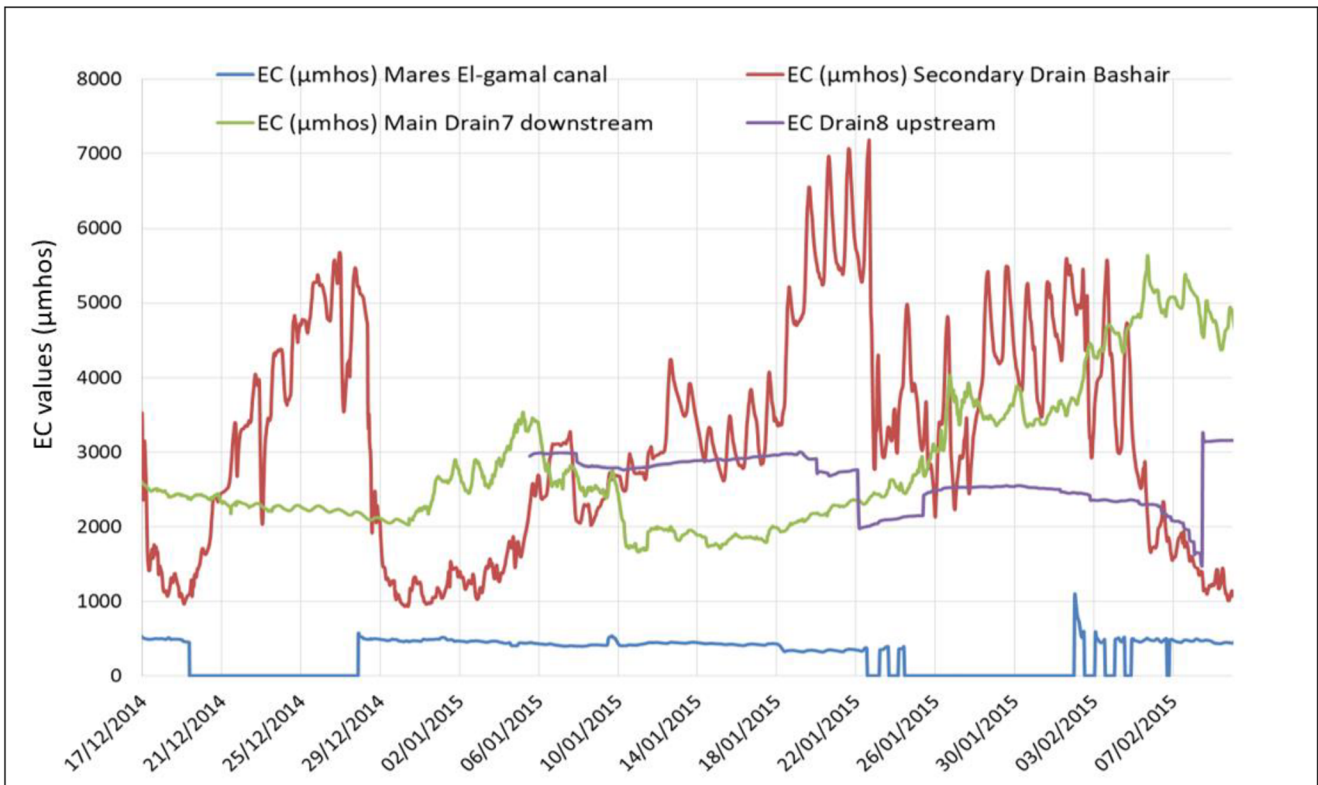


Fig. 9 Comparisons between hourly EC (µmhos) values at canal, secondary and main drains

temperatures become lower in winter (16 to 25°C) (Fig. 10a and b). These results showed that DO was most of the time not meeting standards, especially in main drains that collect not only agricultural drainage but also untreated household

sewage water. Secondary drains collecting only or largely agricultural drainage water displayed better DO values. Many studies noted that the Egyptian drainage system is loaded with great amounts of untreated municipal and wastewater from

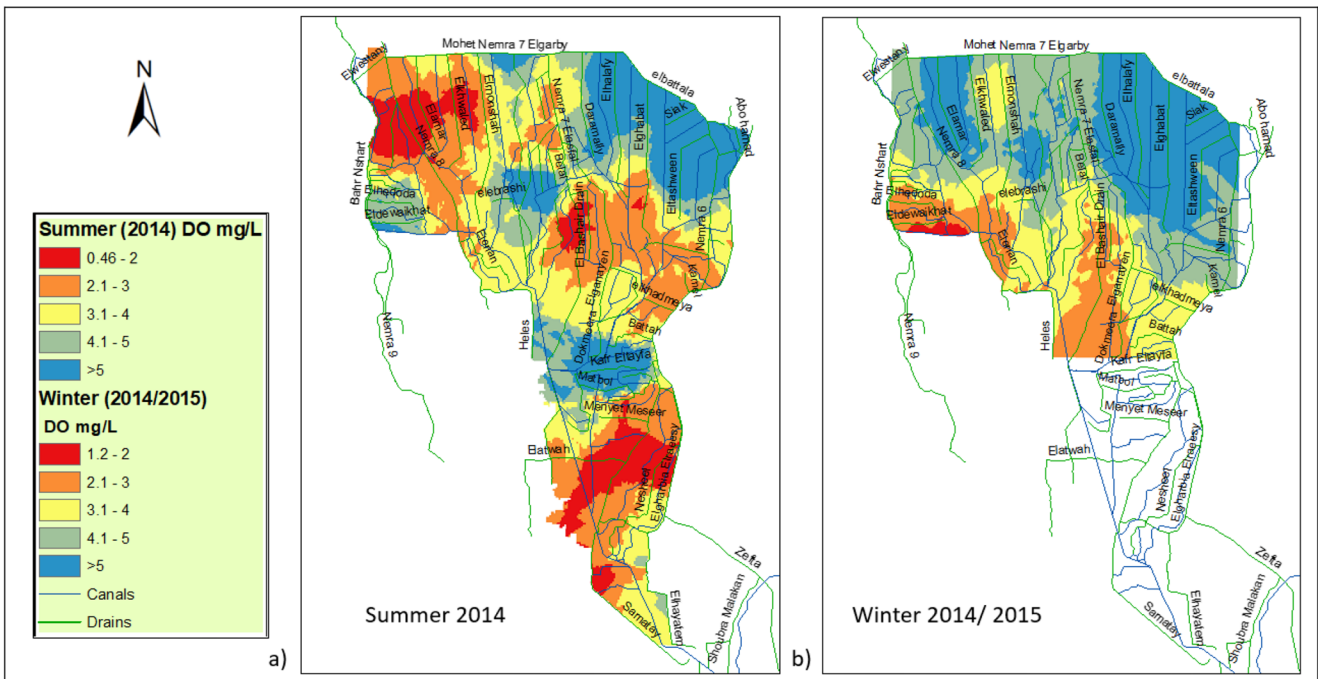


Fig. 10 Spatial variability of DO (mg/l) values in the study area

villages and cities, in addition to fertilizers which is a serious threat to the quality of irrigation and potable water supply (Ritzema 2009; Abdel-Gawad 2004; Abdel-Azim and Allam 2005; Wolters et al. 2016; El-Bana et al. 2017). According to legal norms and the government’s reuse strategy, these findings would prohibit drainage water reuse, yet the practice continues in various locations given a limited oversight capacity.

Both farmers and the state resolve water shortage in the Nile Delta by pumping water from drains. The MWRI started to expand this practice on a large scale some 40 years ago by establishing around 21 major stations to pump water from the main drains into the main canals (Abdel-Azim and Allam 2005). Unfortunately, several of these pump stations are now left idle, because the gradual water quality degradation in these drains made this drainage water unfit for further mixing with canal water, as the canal water is used by downstream cities for domestic consumption. As a result, the ministry’s strategy evolved toward considering reuse pump stations set up in secondary drains to support secondary branch canals (“intermediate drainage reuse”). Applying the reuse idea at the secondary level makes it possible to reinject the water into the system that is possibly not yet (too) polluted for agricultural reuse or to do it in canals in which there is no intake for domestic water treatment stations. Our study area has 28 stations of different sizes, which are mostly used in the summer season from May to August (IWMI and WMRI 2013). In addition, 2500 individual pumps were used by farmers in the summer season to supplement irrigation from the drains

(Molle et al. 2015). According to our results, for the northern part of the Nile Delta, secondary drains had higher salinity and better DO values than main drains, and then reusing its water would have adverse impacts on both soil and crop productivity. Therefore, salinity levels, dissolved oxygen, and other pollution indicators should be considered while taking a decision of reusing drainage water.

Variability of pH

The high and low pH values of drainage water can be an indicator of increasing pollution as it affects organisms living in the water. Factors affecting pH are soil compositions, organic materials, chemicals, and acid precipitation within the water body. Acid precipitation can occur due to alkaline gases, ammonia, and calcium emitted from anthropogenic and natural sources (Daifullah and Shakour 2003). Water having pH less than 7 is considered acidic water, while pH greater than 7 is alkaline water (USGS 2018). As mentioned before, standard levels of allowable drainage water quality for reuse in agriculture require a pH between 6.5 and 8.5. The measured values of drainage water pH in our study area varied spatially from 7.45 to 8.39 in the summer season and increased slightly in the winter season with values from 7.81 to 8.50 (Fig. 11). We do not have a satisfactory explanation of high pH values, but these values are considered normal for irrigation purposes (Ayers and Westcot 1976).

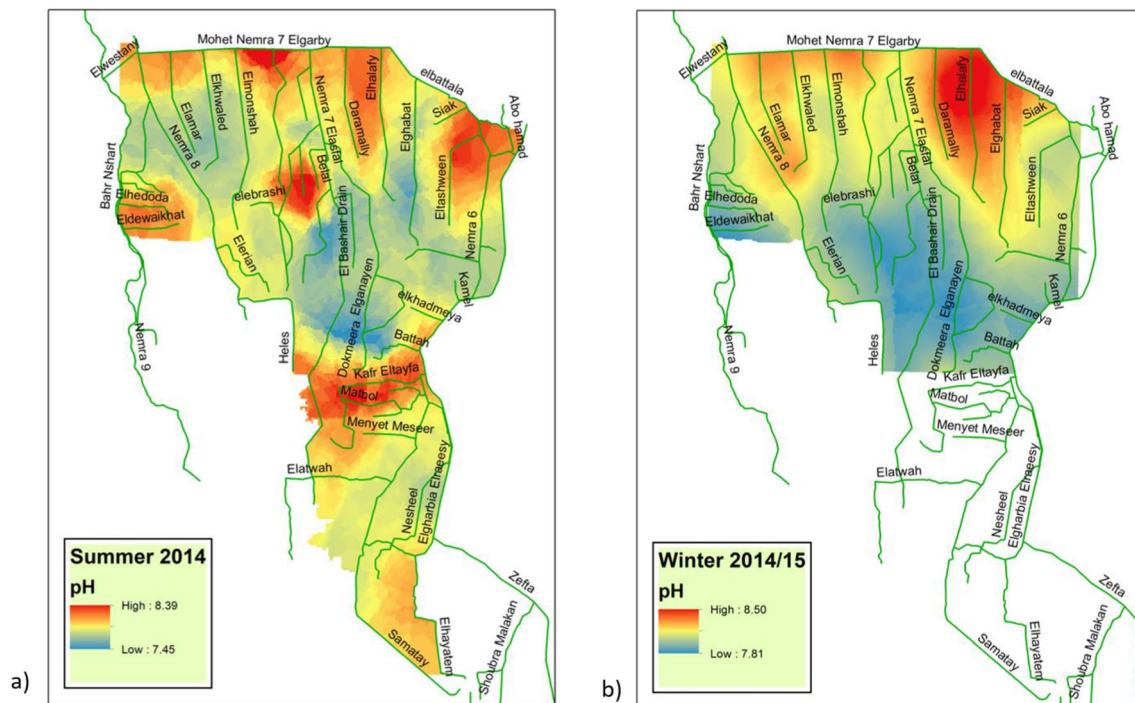


Fig. 11 Spatial variability of pH values in the study area

Conclusion

This study draws several conclusions from the measured spatial and temporal variability of drainage water quality at multiple scales in the research area. The drainage water salinity in the collectors of the subsurface system varied widely with depth, space, and time, which among others reflects soil heterogeneity, but also how soil salinity increases dramatically when the subsurface drainage is clogged up and not working. Also, secondary drains located in the northern part of the Nile Delta had the highest variability of EC values due to collecting salts from deeper soil layers and seepage of saline groundwater at the time of low-flow discharge. In our study area, this increased the salinity in secondary drains up to four times that of water coming from the collectors.

The literature suggests that high salinity levels in the drainage system are a consequence of multiple reuses across the Delta (El-Ganzori et al. 2000; Hussain et al. 1995; Abbott and El Quosy 1996). Although reuse does indeed increase the concentration of salts, it appears that this phenomenon is (largely) secondary to that of the production of salt by capillary rise and interception of groundwater in the northern part of the delta. This coastal area corresponds to former marshes that have been reclaimed over the past 50 years. Resulting from centuries of tidal flows with brackish water and sedimentation between the Nile River and the Mediterranean Sea, the soil profile in this area has accumulated large quantities of salts. When irrigation and drainage water decrease in winter, these coastal soils release salts when the upward seepage of groundwater occurs. This level of salinity is problematic for crop production (Aydin et al. 2015; Parihar et al. 2015) and hinders the reuse of drainage water at the tail end of the study area that suffers from water shortage. This phenomenon also means that the strategy of rice cultivation in the summer to add more freshwater and enhance the soil in the northern part of the Nile Delta only solves the problem of salinization if it is permanently pursued. Controlling water levels in the secondary drains can help reduce the seepage of saline groundwater and consequently water salinity. The design depth of secondary drains should not exceed the depth needed to capture drainage water from subsurface collectors. Also, drainage water salinity can be locally very high when subsurface drainage is not functional or the drain is draining deep layers, with important consequences on local reuse. This constraint also affects the northern part of the delta where salinity is constantly enhanced by upward seepage. Therefore, we do not recommend reusing drainage water at the secondary level in the Northern Nile Delta to protect the land from salinization and crop productivity reduction.

Moreover, DO values were most of the time not meeting standards for reuse in irrigation, especially at main drains that collect not only agricultural drainage but also untreated household sewage water. This suggests high levels of fecal coliform

affecting the water quality (El-Bana et al. 2017). The reuse of drainage water occurs mostly in summer from May to August using both main and secondary drains despite the low quality of drainage water. The treatment of wastewater coming from cities and villages becomes essential, as well as regular monitoring of water, plants, and soils to protect them from contamination and benefit human health (Ahmed and Slima 2018). Drainage water pollution does not only affect crop productivity but also human health, soil quality, aquaculture, and lake biodiversity. Secondary drains collecting only or largely agricultural drainage water exhibited better DO values. In addition, pH values were normal for irrigation purposes at all studied levels.

In summary, salinity and quality of drainage water in the Nile Delta vary highly with space and time, and irrigation water management can play an important role in controlling the salinity and pollution levels in drains. Our methodology of monitoring the drainage system at different scales from plot to system levels enables us to specify the relation between studied drainage scales and indicate sources of pollution. Therefore, further monitoring research of other water quality parameters that were not covered in our study is necessary to complement the available macro-level picture. In addition, continued measurement of drainage water salinity using fixed sensors shows that temporal variation at the plot and secondary drain levels is significant especially in winter. Spatial and temporal monitoring of the water quality at different scales of the drainage system is essential to refine the government's drainage reuse strategy to increase water availability and reduce adverse effects of reuse.

Acknowledgements This research has been conducted with funding from Australian Centre for International Agricultural Research (ACIAR) under project N. LWR/2011/045 titled “Management of water and salinity in the Nile Delta”. The authors would like to thank the National Water Research Centre (NWRC) and notably the Water Management Research Institute (WMRI) and its technical staff in Kafr El-Sheikh for their collaboration in the data collection.

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